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Data Discovery, Caching, Security and Architecture Support in Edge Computing

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Outline

- Pervasive edge computing (PEC)
  - Motivation and concept
  - Challenges, opportunities and solution
- Data discovery and retrieval in PEC
- Data caching in PEC
- Blockchain for secure data caching in PEC
- Architecture support for PEC
- Future research agenda in PEC
- Summary

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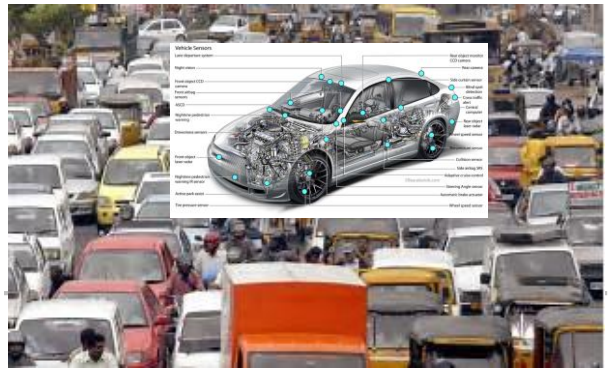
Emerging Edge Devices

- Various devices of rich, diverse resources
  - phones/tablets/wearables, IoT, vehicles
  - perform sensing, communication, storage, processing operations
- Pervasive, high density distribution everywhere by opportunistic congregation
  - customers in cafes, passengers at boarding gates
  - IoT devices in homes, offices, shopping malls
  - vehicles around city streets



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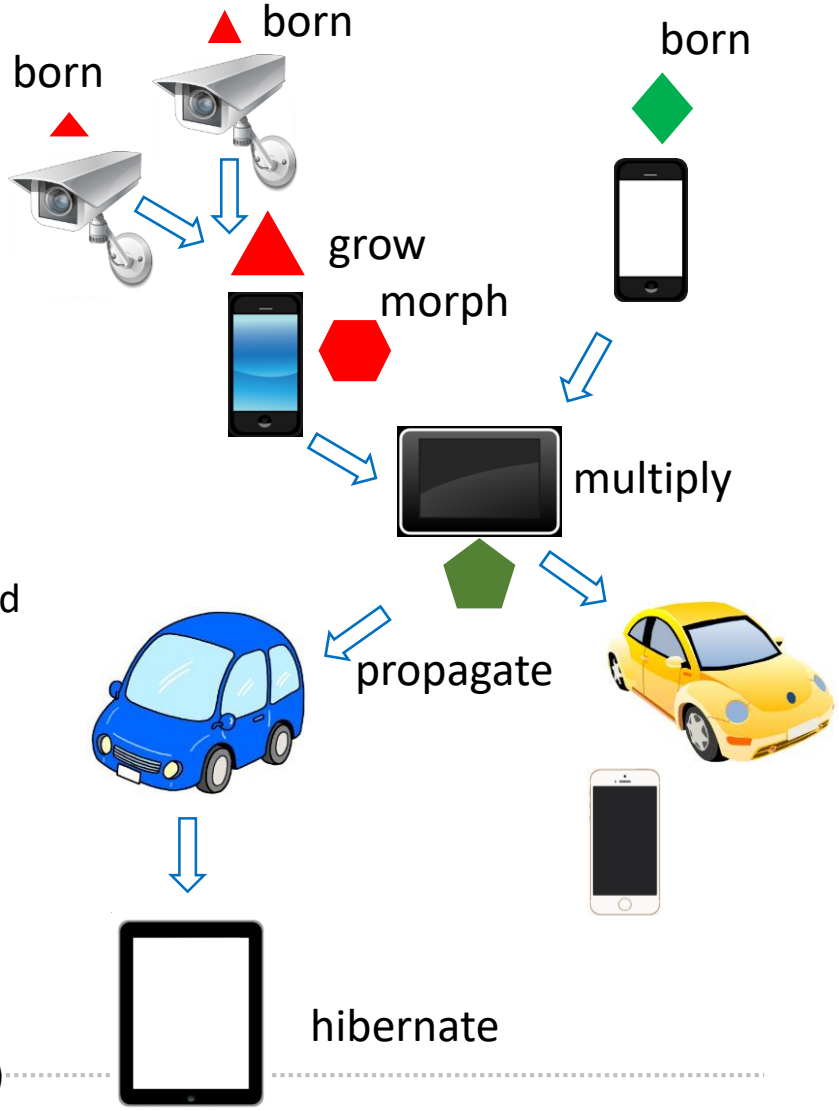
New Computing Paradigm: Pervasive Edge Computing (PEC)

- Data storage /processing and decision all are performed at the edge
  - Contrast to cloud computing where the edge provides only data, but storage, processing and decision are done in the backend
- Promote data as **first class** citizens
  - Data become **independent** entities decoupled from specific devices (e.g., their producers)
  - Same/similar data/resources can be provided by different devices
    - Whichever willing/capable should be used
- Data become **living** organisms
  - born (gathered by sensors)
  - grow (accumulated over space/time)
  - morph (transformed in syntax/semantics after processing)
  - multiply (information extracted by merging different data inputs)
  - propagate (disseminate)
  - eventually hibernate/die (archived/eliminated)



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Advantages of PEC

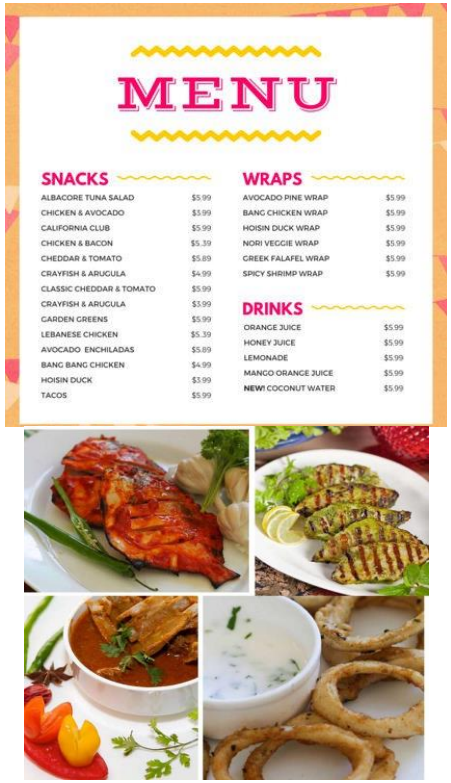
- Zero barrier
  - No infrastructure cost/complexity in deploying, maintaining dedicated cloud backend
- Low latency
  - No need to communicate with cloud. Processing occurs near data, greatly reducing back-and-forth transmission delay
- Connectivity independence
  - No internet necessary. Communication among peer devices even without the Internet
- Democratic creativity
  - No central authority. Devices are free to decide with which others to collaborate and how, enabling flexible and diverse applications

Challenges and Opportunities in PEC

- Challenges
  - Heterogeneity: types/quantities of device capability/resources vary greatly
  - Uncertainty: highly dynamic changes in mobility, connectivity, resource availability (sensing/computing/storage/communication)
  - Diverse ownership: no central authority, mostly voluntary sharing
- Opportunities
  - Pervasive distribution: devices everywhere
  - Existence of more powerful devices: vehicles, main powered, to help coordinate peers and perform intensive work for others

Peer Data Sharing (PDS)

- Discover nearby, opportunistically available data, and retrieve them
  - avoid blindly requesting non-existent data
- Peer Data Discovery (PDD)
  - Build a “menu” of available data
- Peer Data Retrieval (PDR)
  - Retrieve desired data



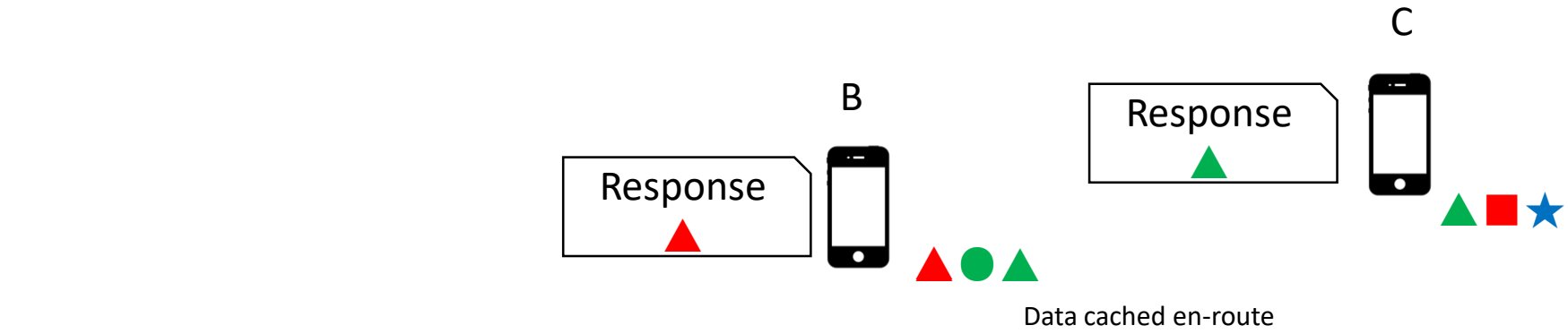
Data as Independent Entities

- Data are self-sufficient entities decoupled from original producers
  - widely cached, thus referenced, stored and accessed from any willing and capable devices
- Data Descriptors
  - When produced, each data item is associated with a **data descriptor** (a metadata entry)
    - Metadata is also a kind of data
      - Widely cached, possibly separately from respective data
    - All such entries together describe what data *may* exist in the environment (the menu)
  - One possible form: key-value pairs
    - {key: value}
    - Example
      - Data Type: **NO_2** sample
      - Attributes: **time** and l**ocation** of sample
      - Namespace: **environment monitoring/atmosphere**

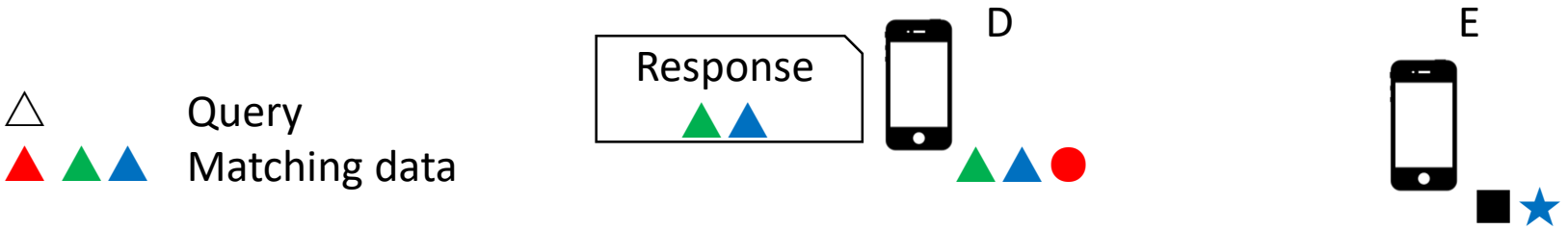
Data Query, Response and Caching

- A consumer sends **queries** to specify desired data and retrieve them from other devices
- Queries propagate over the network towards desired data
  - Flooded if no routing information for the data exists (e.g., newly generated data)
  - Otherwise, follow content-centric routing to reach the data (explained later in PDR)
- Response
  - A provider sends **responses** to return data that are requested by queries
  - Responses are delivered back to the consumer following the reverse path of the query
- Caching
  - Intermediate nodes can cache the data for future requests
    - Shorter access latency for future requests
    - Better robustness to uncertainty (e.g., node mobility, connectivity failure)

Query, Response and Caching



1. The consumer propagates a query
2. Each device includes matching data in its response
3. Responses follow reverse path to reach the consumer, and their data may be cached en-route



Peer Data Retrieval (PDR)

- Once the "menu" of data descriptors is retrieved, the consumer decides which data items to "order"
- Two typical scenarios: large and small data
  - Scenario 1: a large data item (e.g., a video clip) consisting of many small **chunks**, each cached by multiple devices.
  - Scenario 2: many small data items cached by multiple devices (e.g., air pollution samples in certain area).
- We focus on Scenario 1. Scenario 2: follow the same process as metadata discovery discussed earlier
- **Question: How to obtain a copy of each chunk quickly and efficiently?**

Two-Phase Data Retrieval

- Phase 1: Building content-centric routing tables
- Phase 2: Recursive chunk retrieval

- Content-centric routing table
  - Each routing entry at a node {data_chunk_ID, m, n_{ID}}

    tells how far in minimum hops **m**, via which neighbor(s) **n_{ID}** to reach a chunk **data_chunk_ID**

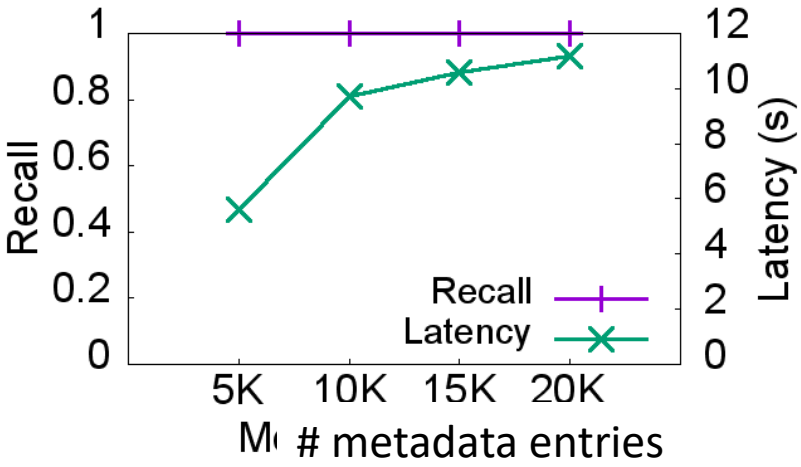
Creating Routing Tables

- Phase 1: Routing Table Creation
  - A consumer propagates a query for routing table entries of desired data D
  - A node M_0 with desired chunk i responds: {D-i, 0, -}
  - At hop k, node M_k adds a local routing entry: {D-i, k, M_{k-1}}, and continues forwarding this entry towards the consumer
  - Finally at the consumer: via which neighbor, in how many hops to reach the nearest copy for each chunk

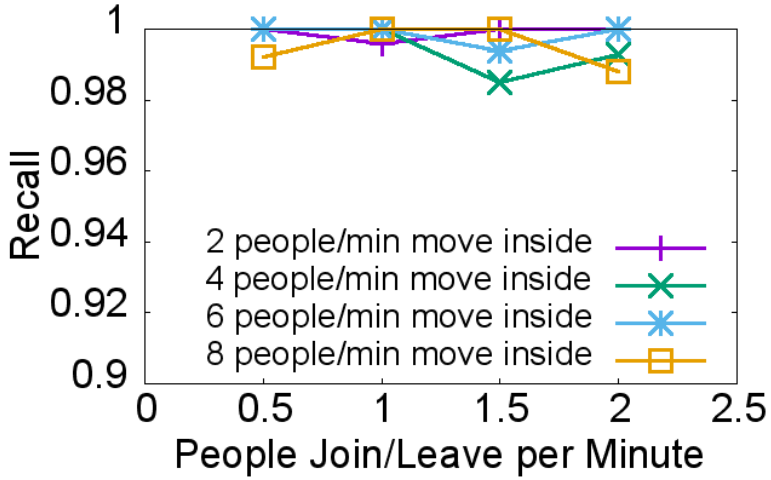
Recursive Chunk Retrieval

- Phase 2: Recursive Chunk Retrieval
  - A consumer **sends** sub-queries, each requesting a subset of chunks from a **direct neighbor**
  - Upon receiving a sub-query, a node
    - **replies** requested **chunks** it has
    - **divides** remaining chunks into sub-queries, then **sends** to neighbors with minimum hops to those chunks
  - Upon receiving replied chunk, a node **forwards** it back towards the **consumer**
  - Chunks are retrieved recursively from all downstream nodes
- Use an algorithm to balance the load among neighbors to shorten retrieval latency
  - Some neighbors on shortest paths send more chunks, thus more workload
  - Objective: minimize the maximum load among all neighbors
  - First assign each chunk to a neighbor with smallest hop count
  - Heuristic: move a chunk from the neighbor with highest load to the neighbor with the 2nd shortest path; repeat until the highest load no longer decreases

Data Discovery Completeness and Latency



- 100% discovery in a few seconds



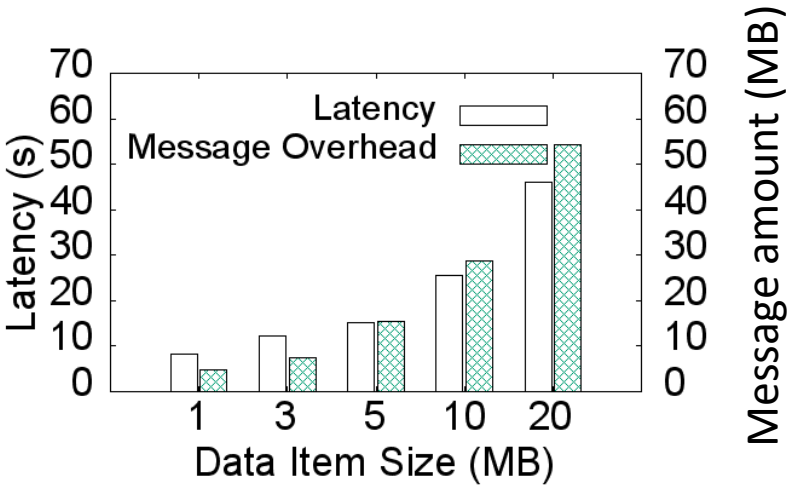
- 100% discovery despite mobility

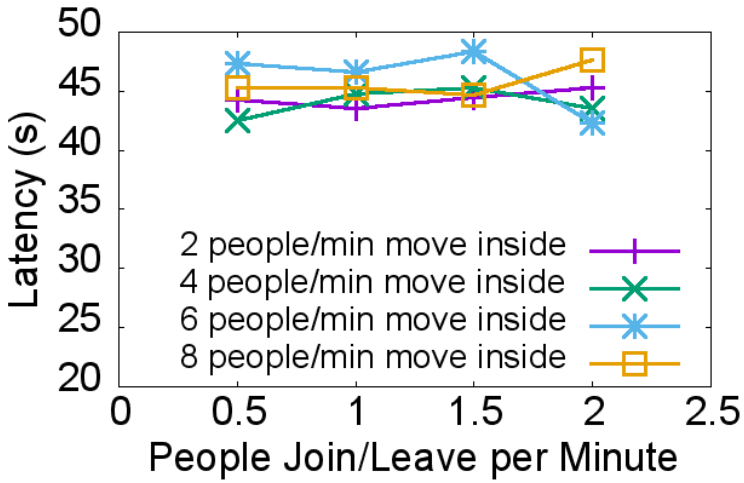
Observation: PDD discovers all metadata entries in short time despite mobility

Setup:

- 100 node network
- Simulation parameters based on an Android prototype
- Mobility based on 8 hours of real world human movement observation

Data Retrieval Latency





- 10's of seconds for 10-20MB data;
- Retrieve nearest copies in 2-3 hops (message amount 2-3 times of data size)

- Latency unchanged despite mobility

Observation: PDR retrieves large size data in short time

Data Caching

- In PEC, a node stores a copy of data it forwards, overhears, or receives
  - The node itself may not need the data
- Benefits
  - Cached copies can be used to meet consumer needs
  - Less latency: nearest copy sent
  - More robustness: copies exist after some node failure/mobility
  - Higher bandwidth: different portions of the same data can be retrieved from multiple copies
- Question: **Which node should store a copy of data**?

Limitation of Existing Caching Work

- Fairness in workload is not considered
  - Assume all nodes obey one authority (e.g., owner of the whole network)
  - Some ``best'' nodes are dictated to shoulder more caching workload than others
  - Node ability and willingness are not considered
- In edge computing, no central authority exists
  - devices belong to different owners; each has limited resources and wants to control its resource contribution

Metric for Caching Fairness

- Fairness Degree Cost
  - The less resources, the higher the cost, thus less willing to cache more data
  - One simple form
    - $f = \frac{storage\ used}{storage\ available}$
- Intuition: put data on nodes with more available resources, thus lower cost

Metric for Contention Cost

- Wireless contention causes delays in data access
  - Collisions due to multiple nodes send simultaneously, thus loss of messages
  - Back-off time, retransmission add to the delay
- Contention induced-delay cost
  - Quantify contentions along data delivery path between nodes i and j
  - Proportional to total amount of data messages along the path

Cache Placement Problem Formulation

- Problem: Given a network topology, for each data chunk, determine which nodes should cache a copy
- Objective: Minimize a weighted sum of fairness and contention costs
- Placement should achieve **fairness** (similar loads among nodes) while minimizing contention (thus retrieval **latency**)
- An integer programing problem is formulated
  - Map to multiple Connected Facility Location (ConFL) problems added together
  - ConFL problem is an NP-hard problem, thus, our problem is also NP-hard

Centralized Approximation Algorithm

- The algorithm adopts a 6.55-approximation algorithm of ConFL problem as a subroutine
- It preserves the approximation ratio
- Complexity is $O(N^3)$, *N:* number of nodes in the network
- Limitation: require global information at each node

Extend to Distributed Algorithm

- Each node needs to decide individually whether or not to cache
  - The centralized approximation algorithm requires global information, which is difficult to obtain
- Basic idea of distributed algorithm
  - Each node asks other nodes within k hops whether they can help cache the data
    - k is a preset parameter, e.g., 2-3
  - If a node receives more `yes' responses, it is more likely to cache data
- Message overhead: $O(QN + N^2)$
  - Q: number of data chunks cached
  - N: number of nodes

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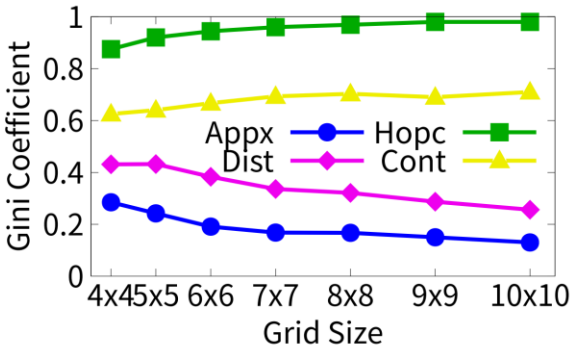
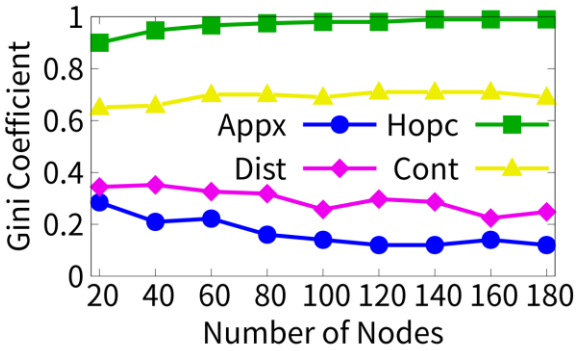
Fairness Evaluation

- Compare with two existing algorithms:
  - Contention based (Cont): minimizing total contention cost
  - Hop count based (Hopc): minimizing total transmitted hops
- Gini coefficient is a common metric to quantify (in)equality in a set of values
  - Value between 0-1: the smaller, the better (fairer)



(a) Grid network



(b) Random network

- Our algorithms (Appx/Dist) achieve much better fairness than two existing algorithms (Cont/Hopc)

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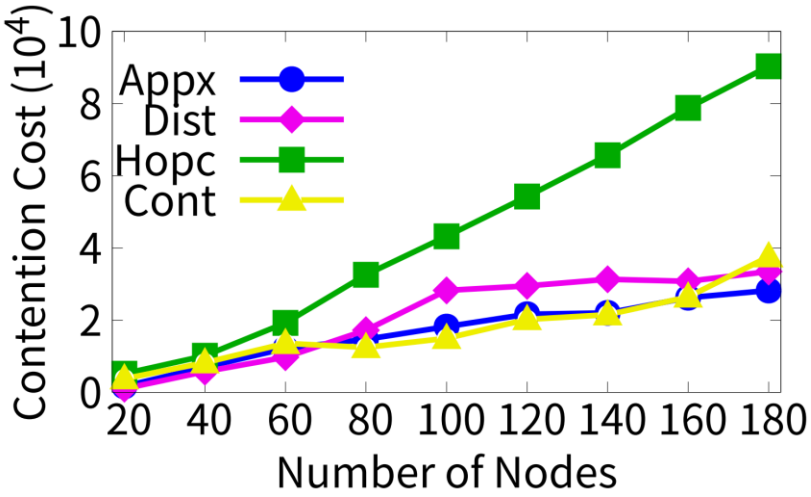
Contention Cost Evaluation

- Contention-induced delay cost on random networks



- Minimum contention cost
  - Our algorithms are comparable to Cont, which has minimum contention cost
  - Our algorithms are much lower than Hopc
- **Observation**: our algorithms achieve minimum contention cost while greatly improving fairness

Secure Data Caching in PEC

- A major concern in edge computing: **security**
  - Data transactions and privacy protection in an edge computing environment often have to involve a trusted third-party
- **Blockchain** is a promising technology to combat this challenge. It can be used to ensure data transactions unmodifiable and undeniable
  - A blockchain system consists of a chain of blocks (records). Each block contains the hash result from its previous block to form a chain
  - Blockchain has many security features over a regular distributed system
    - keep complete transaction history
    - designed against data modification
    - No need for a trusted third-party in the transactions and can avoid “a central point of failure”

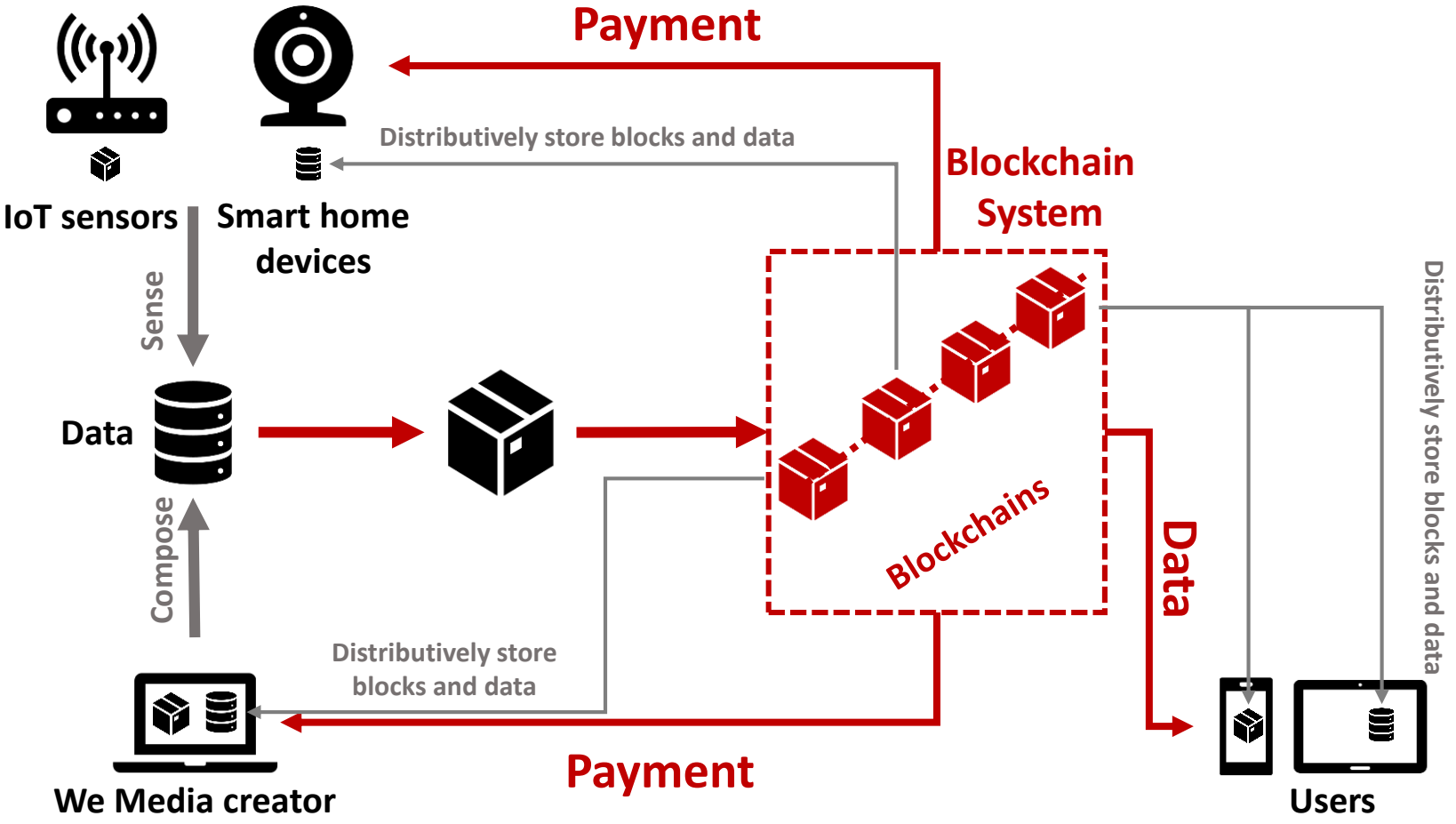
Blockchain on Edge

- Combining blockchain with edge computing can have many advantages that ensure
  - **Secure payment**: Every transaction is recorded in the blocks, thus cannot be changed or denied
  - **Access-control:** Data producers can directly manage subscriptions to deliver for-profit data to consumers
  - **Privacy**: Blockchain can protect the identity of the users
- Challenges
  - Limited resources, e.g., storage, computing power
  - Resource constraints of edge devices reduce the applicability of blockchain
    - Storing all blocks and data on every edge node is not feasible
    - Edge devices have less computing power and energy capacity compared to traditional blockchain miners
- Directly applying the existing blockchain approach onto edge is not feasible

Blockchain on Edge - Our Approach

- Design a blockchain system suitable for edge environment, focusing on reducing storage, latency and energy cost
  - Instead directly storing data in blocks, only store metadata in blocks, and distributively store data and blocks in key locations for quick access
    - Data can be searched through metadata, and can be accessed from nearby cached nodes
    - Blocks are also distributively stored among nodes
  - Adopt **Proof of Stake (PoS)** consensus mechanism to achieve consensus among nodes to reduce energy cost
    - It does not require a compute-intensive process to achieve consensus as **Proof of Work (PoW)** consensus mechanism

Blockchain on Edge - System



Fair and Efficient Storage Distribution

- After metadata are created and stored in blocks, data items are then stored onto nodes distributively
  - Metadata contain where the data item is stored and users can access the data based on the information
- Some nodes in critical locations can be accessed easily. Such nodes will store data items for other nodes to access
- Fair (balanced) storage enables more nodes to participate in caching and avoids overloads
  - Nodes with more resources and at key locations are more likely to be selected to store data and blocks

Recent Block Storage

- Edge devices, often with wireless transmission and mobility, may miss newly generated data and blocks
- Recently accessed blocks are more likely to be requested and more vulnerable to temporary disconnection of nodes
  - If recent blocks are more pervasive in the network, it is easier to retrieve them
- Nodes are required to cache a certain number of most recent blocks and replace the blocks using FIFO
  - The number of recent blocks a node caches also depends on the locations and fairness

Consensus Mechanism (PoW)

- A blockchain system needs a consensus mechanism to achieve distributed consensus on new block generation

Proof of Work is a commonly used consensus mechanism, e.g., Bitcoin

- Miners compete to find a certain value, when hashed together with the whole block, the hashed value satisfies a certain target value
- Very time and energy consuming process
- Relatively secure, if more than half of nodes in the system are honest

Consensus Mechanism (PoS)

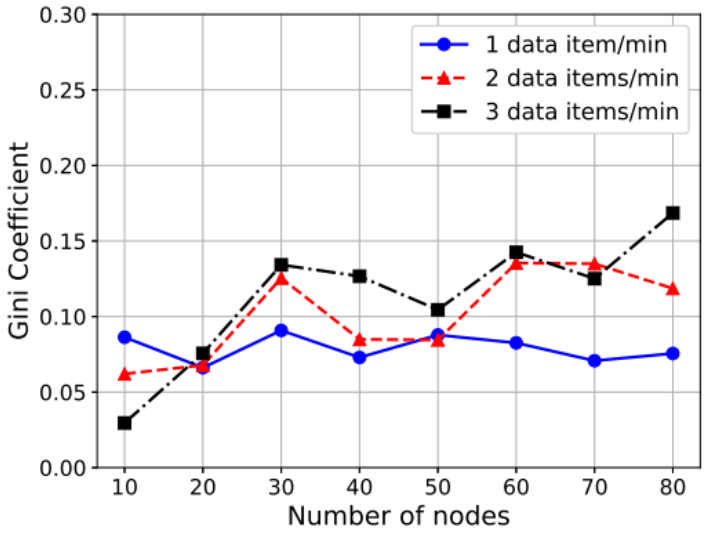
Proof of Stake (PoS) is another commonly used consensus mechanism

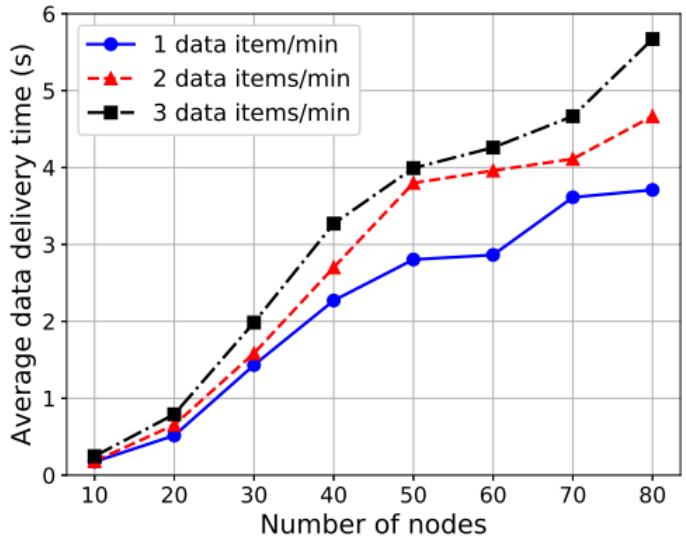
- Some cryptocurrencies have adopted this idea, e.g., Peercoin
- Creator of the next block is randomly selected based on the stake, e.g., wealth, age, contributions
- Less time for devices to compute and reach consensus
- Maybe less secure compared to PoW
- More practical to implement PoS in edge environment

Proof of Stake

- **Selection rule**: If a node contributes more, i.e., storing more data and creating more blocks, it will have a higher probability than others to be the creator of the next new block
- We reward the node that has contributed more to the system

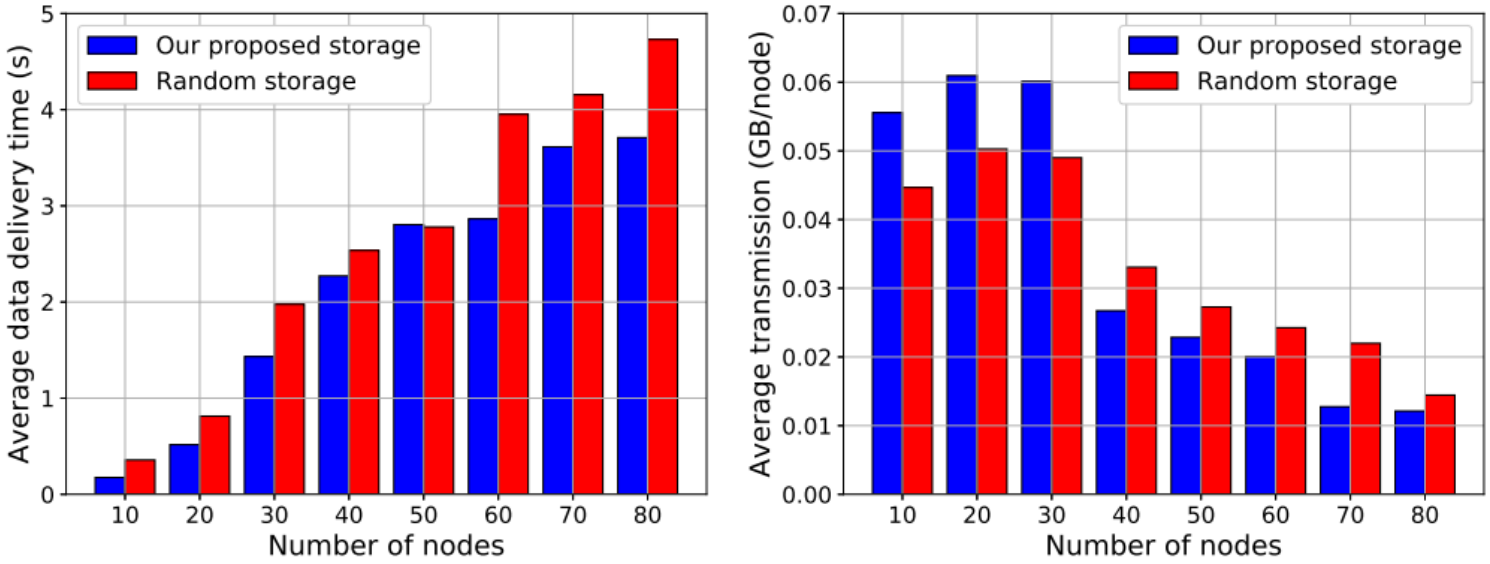
Performance under Different Data Generating Rates





- 1-3 data items generated per minute, in total 500 blocks generated
- Gini coefficient (left) for date storage (load balance) on nodes and average delivery time (right) for different network sizes
- For Gini coefficient, it remains very low among 0.15, showing small disparities among node storage (balanced load)
- Data delivery time grows almost linearly with the number of nodes, and remains almost the same with different data generating rates

Performance under Different Storage Allocation Strategies



- One data item generated per minute, running 500 blocks
- Average delivery time (left) and transmission overhead (right) over different network sizes
- For delivery time, the proposed data storage is shorter than random storage
- The average transmission amount is less when network size is large.

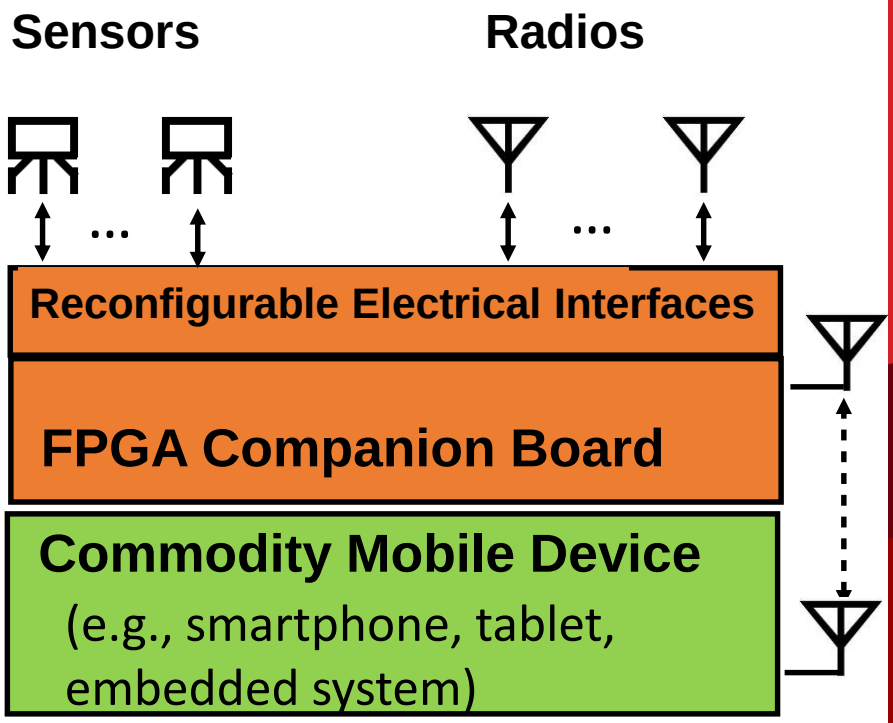
Architecture Support for PEC

- Edge devices exhibit huge heterogeneity: types/quantities of device capability/resources vary greatly
- Many edge applications demand both hardware and software specialization not available on commodity edge devices
- A modular, composable hardware/software architecture for customizable edge devices
  - Diverse modularized FPGA/software computation components
  - Easily composed electronically and computationally like Lego pieces
  - As a companion to augment a commodity mobile device like GPU in a multicore processor

Edge Node Architecture: Towards Low-Cost Modular Specialization

FPGA Accelerator Library
- data/signal processing
- security

Software Computation Component Library



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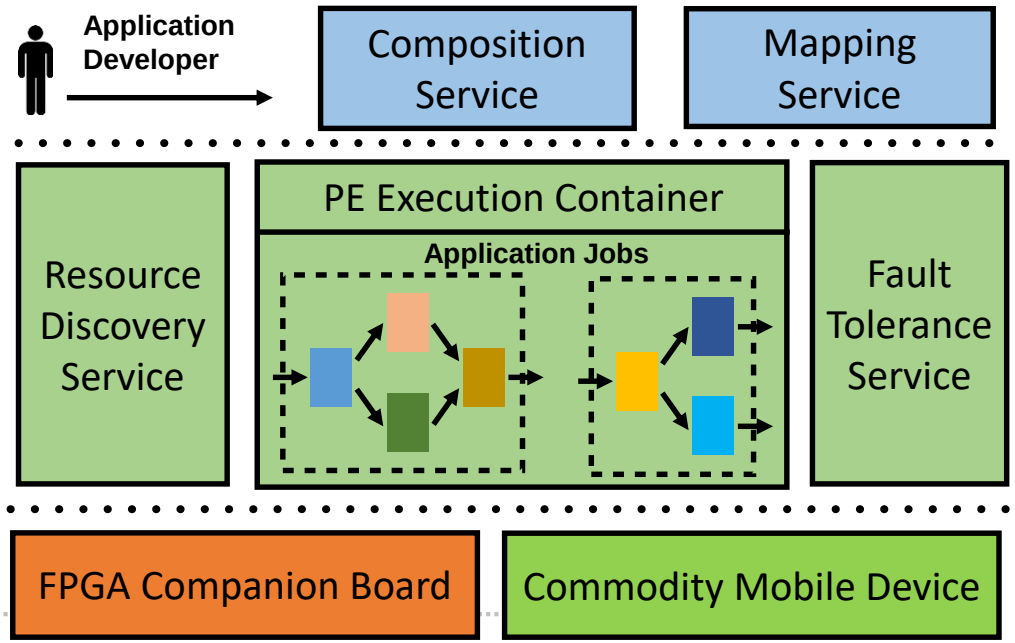
Data Stream Processing System Architecture on Customizable Edge Devices

- A data processing system runs on customizable edge devices
  - **Resource discovery service** finds what hardware/software resources are available in local and nearby edge devices
  - **Composition service** creates jobs in form of connected graphs among modules, using discovered resources
  - **Mapping service** schedules which portions of the graph run on which edge nodes
  - **PE execution container** runs locally deployed application jobs
  - **Fault tolerance service** handles resource variability due to competition/mobility

- Developers compose reusable hardware/software modules and components into applications
- One application may require collaboration and run jobs among multiple edge devices



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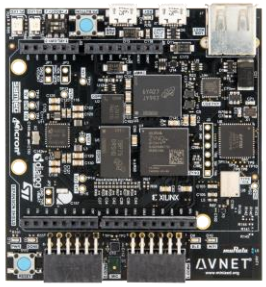
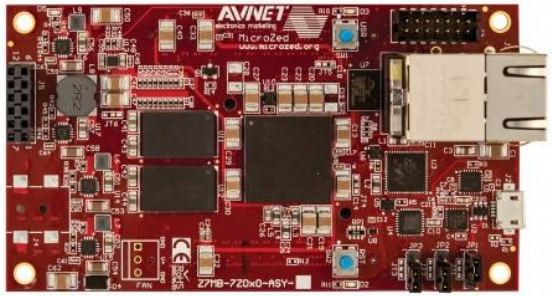
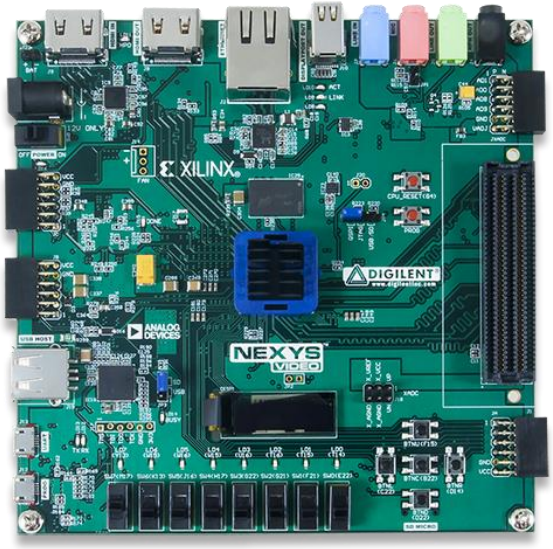
Three Types of “Pebble” Nodes



Socket grade for IoT: Zynq Z-7007S



Phone grade for mobile devices: MicroZed



Tablet grade for vehicles, edge servers:
Nexys Video Artix-7 FPGA

Future Research Agenda in PEC

- Discovery and retrieval at larger scale (e.g., campus)
  - Pure peer based is not scalable
  - Need the help of more powerful nodes
  - Build an infrastructure of more powerful nodes (e.g., static, more resources). They exchange information to store/serve metadata and data for others
- Cache management
  - Aggressive caching: cache anything overheard
    - Reason: storage is relatively abundant while contact is rare, esp. with mobility (e.g., vehicles)
  - How to replace existing data when cache is full
  - Incorprate emerging storage devices
- Autonomous, efficient processing under uncertainty (mobility, connectivity, resources)
  - Nodes automatically decide what processing to invoke where, on what raw data, to produce desired output

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Future Research Agenda in PEC

- Trust management
  - How much trust on whose/what data, on trusted data processed by less trusted nodes, or merged output from producers of different trust levels?
- Security and privacy
  - How to protect against attacks?
    - Attacks are much easier to launch in a loosely coupled environment , like PEC, without central authority or definitive boundary
    - Such as injecting bogus data, claiming others' identities, …
  - How to confine the propagation scope of sensitive data?
- Incentive mechanisms
  - Participation is voluntary. How to compensate contributors (sensing/processing) appropriately to stimulate collaboration?
- Expressive naming structures
  - Adapt semantic web, linked data techniques for more expressive data descriptions based on content, not format
- Smarter edge: machine learning on edge, 5G and 6G devices

Summary

- A new paradigm of pervasive edge computing is emerging
  - Sensing, processing/decision all are done at the edge
  - Sharp contrast to cloud computing
- A data centric architecture offers a viable solution
  - Data as first class citizens
  - Robust and fast data discovery and retrieval
  - Fair cache placement
- Time for exciting research: the field is wide open
  - Architecture support
  - Scalable data discovery, retrieval
  - Cache management
  - Autonomous processing
  - Trust, security and privacy
  - Incentives
  - Semantic data naming
  - Machine learning on edge
  - 5G, 6G edge devices

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Related Publications

- X. Song, Y. Huang, Q. Zhou, F. Ye, Y. Yang and X. Li, ``Pervasive Edge Data Sharing in MANET,'' IEEE INFOCOM/IECCO 2017.
- X. Song, Y. Huang, Q. Zhou, F. Ye, Y. Yang and X. Li, ``Content Centric Peer Data Sharing in Pervasive Edge Computing Environments,'' IEEE ICDCS 2017.
- Y. Huang, X. Song, F. Ye, Y. Yang and X. Li, ``Fair Caching Algorithms for Peer Data Sharing in Pervasive Edge Computing Environments,'' IEEE Transactions on Mobile Computing, pp. 852-864, 2020.
- Y. Huang, J. Zhang, J. Duan, B. Xiao, F. Ye and Y. Yang, Resource Allocation and Consensus on Edge Blockchain in Pervasive Edge Computing Environments. IEEE ICDCS 2019, to appear in IEEE Transactions on Mobile Computing.
- X. Yan, F. Ye, Y. Yang and X. Deng, ``Autonomous Compensation Game to Facilitate Peer Data Exchange in Crowdsensing,'' to appear in IEEE Transactions on Cloud Computing.

Thank you!

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